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Nr. 1. Martin Knudsen: DANISH HYDROGRAPHICAL INVESTIGATIONS AT THE FAROE ISLANDS IN THE SPRING OF 1910

KØBENHAVN
I KOMMISSION HOS C. A. REITZEL
Trykt hos J. Jørgensen & Co. (M. A. Hansteen)
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DANISH HYDROGRAPHICAL INVESTIGATIONS

AT THE FAROE ISLANDS IN THE SPRING OF 1910

(WITH 5 FIGURES IN THE TEXT AND 2 TABLES)

BY

MARTIN KNUDSEN

KØBENHAVN
I KOMMISSION HOS C. A. REITZEL
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1911

In the period from May 10th to June 4th 1910 the Danish researchsteamer »Thor« was staying in the vicinity of the Faroe Islands and in the Faroe—Shetland Channel, in order to undertake fishery and hydrographical investigations under the direction of Dr. Johs. Schmidt. Mr. Sven Palitzsch took part in the cruise as a chemist, and the chlorine- and oxygen-titrations were carried out by him according to the methods usually employed. Mr. Palitzsch undertook moreover a series of determinations of the sea-waters contents of Hydrogen-Ions, based upon the method worked out by Professor S. P. L. Sørensen of the Carlsberg Laboratory.

The stations at which hydrographical measurements were carried on are marked on the chart Fig. 1. On the voyage from Scotland to the Faroe Islands the stations No. 2 up to No. 7 were taken on May 10th, 11th and 12th. The section follows the northern side of the Wyville Thomson Ridge, and shows the distribution of the salinity characteristic of the Faroe—Shetland Channel. The centre of the Gulf-Stream has a temperature of 8,0 ° to 8,5 ° C, which is ca. $^1/_2$ ° C lower than usual in the beginning of May. There is, however, nothing very unusual in the distribution of the temperatures, and as extensive researches have also been undertaken on the part of Scotland on more north-eastern lines, it will be natural to postpone a more detailed treatment of our measurements till the Scotch observations have been published.

However, some of our stations have been repeated at short intervals; they offer a good picture of the hydrographical changes which may take place in the Faroe—Shetland Channel during a short period, and in the following we shall pay special attention to these investigations. It is evident that in order to draw with any certainty conclusions for the future from the variations found from one season to another or from one year to another, we dare not ignore the importance of the changes which may take place in far less time. An investigation of this matter was thus urgently necessary, and the beginning which has been made, seems to show that there is every reason to pursue it further in future.

Station No. 7 was taken on May 12th and Station No. 25 on June 1st, 1 mile further East. The positions of the two stations are thus practically identic, and the bottom-depth of 140 metres was also the same at both places. The temperatures and salinities are represented in the following table:

Depth in metres	Temperature		Salinity	
	Da. 7 May 12	Da. 25 June 1	Da. 7 May 12	Da. 25 June 1
0	6,62	7,54	35,20	35,12
10	42		15	
20	42	7,30	15	10
30	40		17	
40	40	6,96	18	10
60	40	81	18	09
80	40		18	
100	40	80	17	10
130	40	81	17	10

We see that the salinity at both stations changes very little from surface to bottom, but from May 12th to June 1st there is a marked decrease in the salinity (a little more than 0,07 ‰) which can

only be explained in the way, that the water has been replaced by some other water. A salinity as low as 35,10 ‰ did not seem to occur in the middle of May, neither South, West or North of the station, for which reason the new water has probably arrived from the North-East quadrant. It has caused the temperature to rise by 0,4 ° at the bottom and somewhat more the nearer we get to the surface, where the increase in temperature amounts to 0,9 °. This rise is not at all slight if we consider that it was accom-

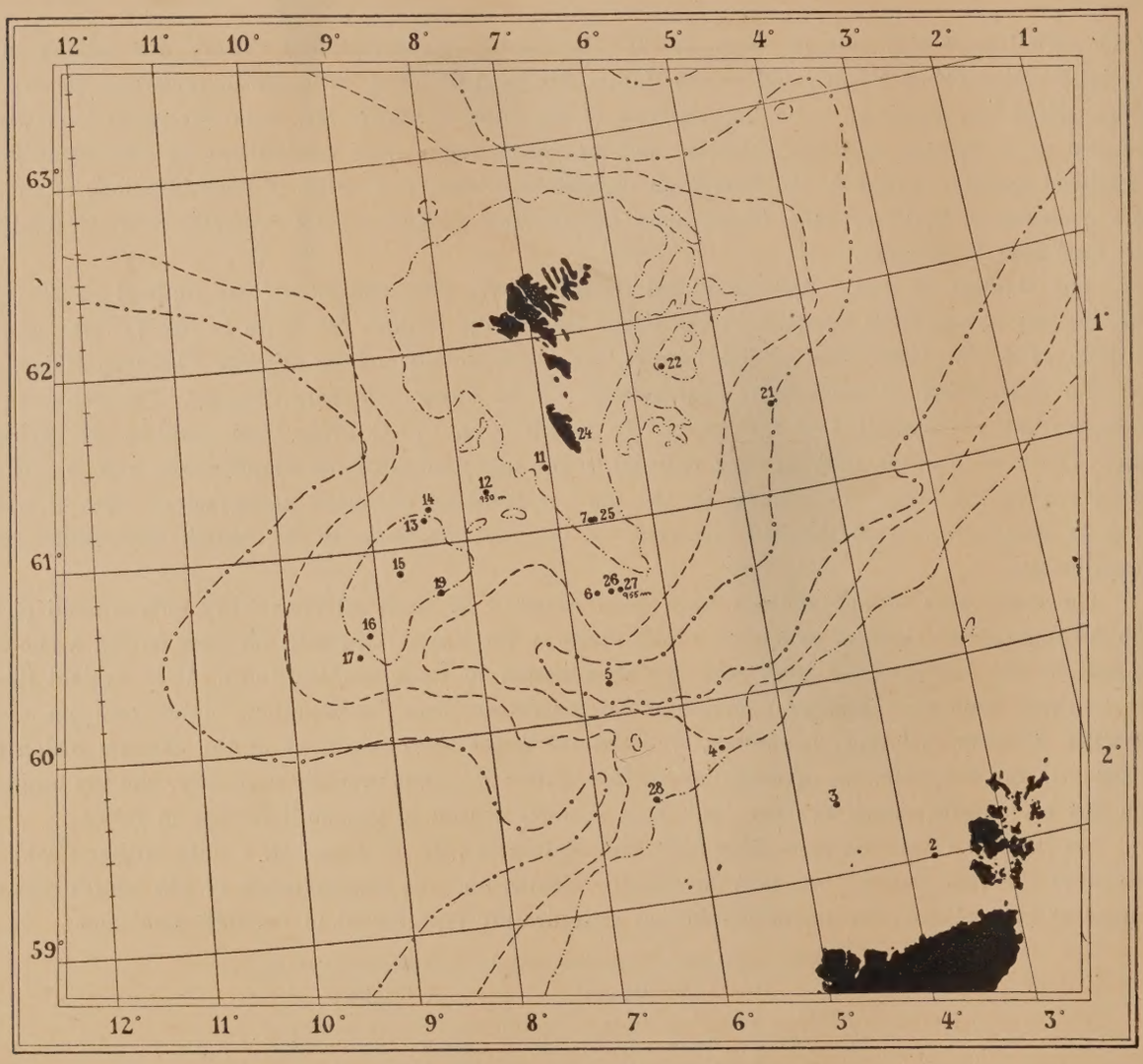


Fig. 1

panied by a decrease in salinity, which in these waters generally causes a decrease in temperature. Thus we have here an example of a current coming from East or North East in an area where the resulting water-movement must ordinarily be presumed to go in the contrary directon, and the current has come from places where the temperature is generally lower than in the locality of the station, but nevertheless we find an increase in temperature extending to a depth of 130 metres.

Thus the hydrographical change which has taken place at the station in 20 days, is rather con-

siderable, and it is greatest at the surface, and yet we shall see that variations of nearly the same size can occur at the surface in a shorter period than 24 hours.

The stations No. 6, 26 and 27 are all situated at the same latitude. Station No 6 is situated 4 miles West of Station No. 26, which again is situated $2^1/_2$ miles West of Station No. 27. Station No. 6 was taken on May 12th, the two others on June 2nd with an interval of only $6^1/_2$ hours. The temperatures and salinities are given in the following table:

Depth in metres	Temperature			Salinity		
	Da. 6 May 12	Da. 26 June 2	Da. 27 June 2	Da. 6 May 12	Da. 26 June 2	Da. 27 June 2
0	6,81	8,70	8,90	35,20	35,18	35,00
10	72			17		
20	65	31	51	17	17	14
30	60			17		
40	54	7,55	20	17	17	15
60	48	6,91	7,93	17	16	16
80	45			17		
100	24	73	36	17	13	16
200	20	26	6,60	17	09	14
250		20			11	
300	20		5,32	17		07
375	15			17		
400			2,93			34,87
950			— 0,80			91

The stations No. 6 and 7 which were both taken on May 12th at a distance of 25 miles, showed the same salinity and about the same temperatures. From May 12th till June 2nd the increase in temperature is the same on Station 6 as on the more northern Station 7, the decrease in salinity is however hardly as great as at the more southerly situated stations 6, 26 and 27, as at 7 and 25.

While the two stations 26 and 27 which were taken quite close by each other with an interval of $6^1/_2$ hours, showed about the same salinity at equal depths, a remarkable difference in the temperatures may be noticed, the water at 60 metres being 1^0 warmer at Station 27 than at Station 26. This difference shows, that the water in the Faroe—Shetland Channel is very heterogeneous, probably because a powerful mixing up of Atlantic water and the other in-flowing waters takes place in the very Faroe—Shetland Channel and its immediate surroundings. The water-volume which at the stations 26 and 27 produces such a considerable difference in temperature, has probably been mixed with water coming either from the East—Icelandic polar current or from the bottom-layer of the Norwegian Sea, and it is likely that the mixing takes place in the way, that very irregular movements, caused by wind and tide, carry water of a lower temperature and of less salinity from the boundary layers of the Atlantic water into the true Atlantic water where it forms »clouds« or »isles« of another temperature and salinity. In this way the heterogeneity arises, and then it again gradually diminishes by further dispersion of the »clouds« until new inflows take place. In whatever manner the mixing-action is going on, the observations show that the isothermes and isohalines must have a very complicated course with many windings and off-shoots, and therefore our hydrographical sections will only in the main give a true picture of the real conditions. But this does not mean that such a picture is without value.

At Station 25, the temperatures and salinities are almost at all depths somewhat lower than at Station 26, which was taken on the following day, and thus it seems that the circulation changing the hydrographical conditions at Station 25 in the period from May 12th till June 2nd, has also extended to Station 26, but to a far lesser degree to the Station 27 close by.

As the differences in temperature at Station 26 and 27 are not combined with corresponding differences in salinity, the specific gravity of the water must be rather different at the two stations. To illustrate this, the following table has been drawn up:

Depths in metres	20	40	60	100	200
Station 26.	σ_t = 27,37	27,50	27,57	27,58	27,62
Station 27.	σ_t = 27,33	27,39	27,43	27,51	27,61
Difference	0,04	0,11	0,14	0,07	0,01

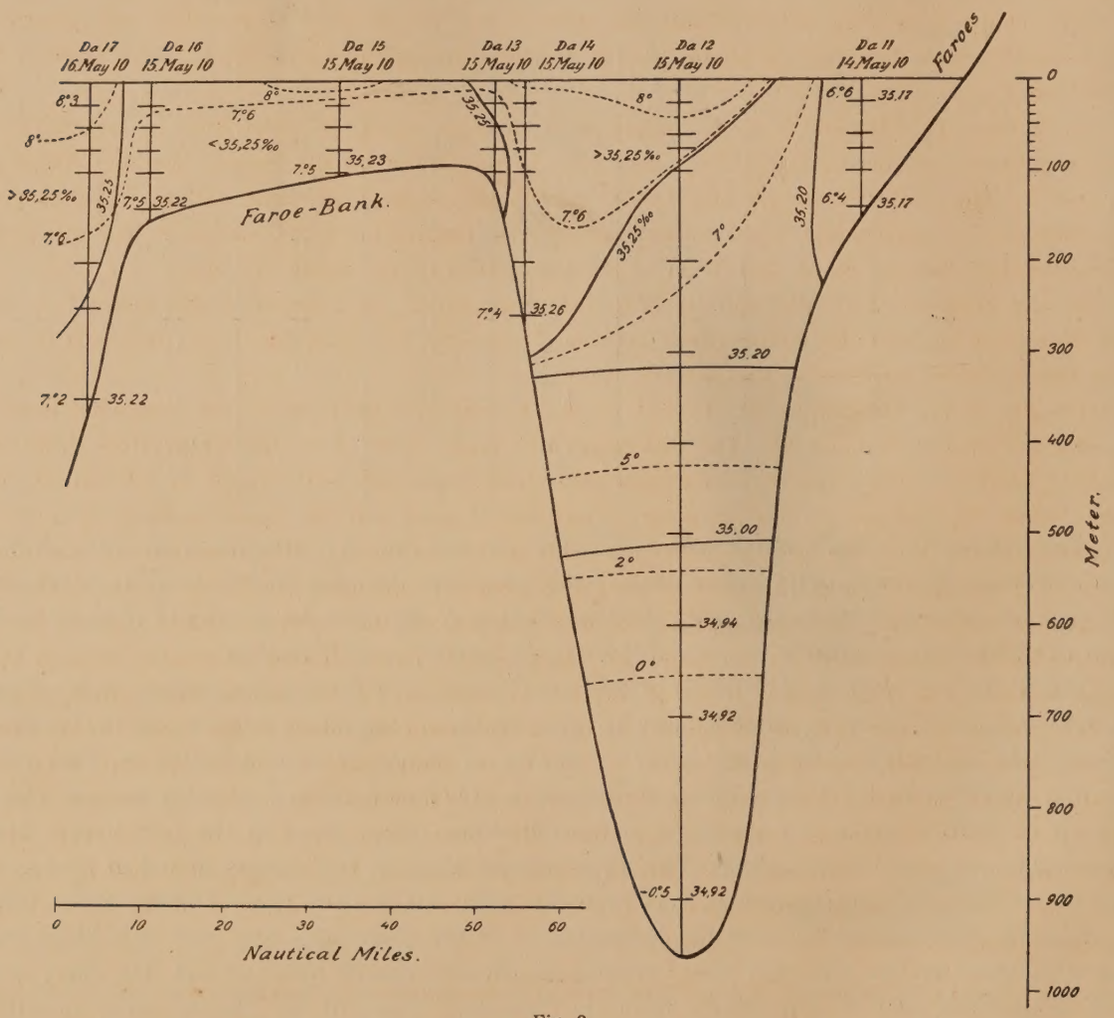


Fig. 2

We see that the difference in specific gravity is only very slight in the upper layers and at a depth of 200 metres, but it shows a distinct maximum at 40—60 metres' depth.

At a depth of 100 metres the differences in specific gravity produce a pressure-gradient of ca. 0,004 Decibar pr. mile, a value, which as far as I know, is greater than any previously found in the open sea. Such a gradient will most likely be accompanied by strong currents and it can scarcely be maintained for a long time.

As will be shown later on, considerable intermediate oscillations in a vertical direction take place in the Faroe—Shetland Channel produced by the tidal force, and it is quite probable that the said differences in temperature are partly due to such movements, our two stations having been taken at an in-

terval of $6^1/_2$ hours. We can, however, scarcely regard the differences as being entirely due to this phenomenon, as certain water-particles then had to rise from 100 metres' depth to 40 metres' depth in the course of 6 hours. This movement would cause the over-lying water to flow away to the sides, and though the bottom conditions would perhaps greatly favour such movements in this place, yet I think it natural to suppose, until the contrary has been proved through direct and repeated measurements, that vertical movements as great as these can hardly occur so near to the surface, and that the observed differences in temperature not only may be ascribed to the difference in time between the two stations, but also and perhaps mainly to difference of place or to a considerable heterogeneity in the water-volumes.

During the days from May 14—16th the stations No. 11—17 were taken; they are situated in a section extending from Suderø in a southwesterly direction across the Faroe Bank. This section is represented on Fig. 2.

At Station 11 situated next to Suderø at a distance of ca. 10 miles from it, the salinity from surface to bottom (150 metres) is 35,17 $^0/_{00}$, the same as was found on the Faroe—Shetland Ridge at Station 6 and 7. The temperatures are also almost exactly the same at all three stations. It thus appears, as if a mixed-up water-volume with proportionately low temperatures and salinities has extended to a very considerable distance South and West of the Faroe-Isles in the middle of May.

At the stations 12—17 the salinity is in the upper layers (to a depth of 300 metres) everywhere greater than 35,20 $^0/_{00}$, and the temperatures between 7^0 and 8^0. We thus find in all this part of the section the characteristic qualities of the Atlantic water.

On the bank, at stations 13, 15 and 16, the salinity and temperature are somewhat lower than at the stations 14 and 17 close by. The difference in average value is for the temperature $0{,}30^0$ and for the salinity 0,034 $^0/_{00}$. The differences are thus only small, especially with regard to the salinity, but on the other hand, the number of measurements is sufficiently great and the results sufficiently uniform, so as to enable us to state the present difference with perfect certainty. This phenomenon was observed earlier on the Faroe Bank [1]), and Dr. Schmidt [2]) met with perfectly analogous conditions on the Rockall Bank.

It is a well-known fact that animal life and vegation in the water on banks such as the Faroe and Rockallbanks surrounded on all sides by deep water, have another character than in the surrounding waters. For this reason it is of interest to examine, if the stated low salinity above the banks can always or as a rule be recognized in the surface-samples, taken on the banks in the course of years. Fig. 3 shows the 100-fathoms' curve of the Faroe Bank, and a dot to indicate each surface observation which has been taken prior to 1910. By the 100-fathoms' curve and an oblique line from NW to SE in the south-western corner of the chart, the observations were, according to their situation, first divided into 4 groups marked: I, II, III, IV, after which group IV was again divided by two dotted oblique lines into three rather equal areas IVa, IVb, IVc. The average salinity $\bar{S}$ of the separate groups were formed, and the result was as follows:

Group	I, NW off the bank,	17	observations	$\bar{S} = 35{,}259$
»	II on » »	21	»	35,272
»	III, SE off » »	37	»	35,304
»	IVa,	17	»	35,290
»	IVb,	29	»	35,303
»	IVc,	15	»	35,319

In the first place, the three groups IVa, IVb, IVc give an idea of the variation in the average salinity in the direction NW — SE in the open ocean; and we see that the variation here is linear.

[1]) Ove Paulsen: Plankton investigations etc. Meddelelser fra Kommissionen for Havundersøgelser, Ser. Plankton I, 8, pag. 30, København 1909.

[2]) Johs. Schmidt: The distribution of the pelagic fry etc. Conseil perm. international, Rapp. & Proc. verb., Vol. 10, pag. 221, Copenhague 1909.

Inside group IV, $\bar{S}_b = 35{,}303$ and $^1/_2\ (\bar{S}_a + \bar{S}_c) = 35{,}305$ are namely of equal size. If the bank had not existed, we might in a similar way have expected, that the average-salinity of group II would also have formed the mean number of $\bar{S}$ for I and III; but it is not so. Thus we find that $\bar{S}_{II} = 35{,}272$ is 0,010 ‰ less than $^1/_2\ (\bar{S}_I + \bar{S}_{III}) = 35{,}282$. Although $\bar{S}_{II}$ is not less than both $\bar{S}_I$ and $\bar{S}_{III}$, the circumstance that $\bar{S}_{II}$ is less than the mean of $\bar{S}_I$ and $\bar{S}_{III}$, seems to indicate, that the presence of the bank exercises a diminishing influence on the surface-salinity, as this on the bank is probably less than the value it would have had in case the bank had not existed.

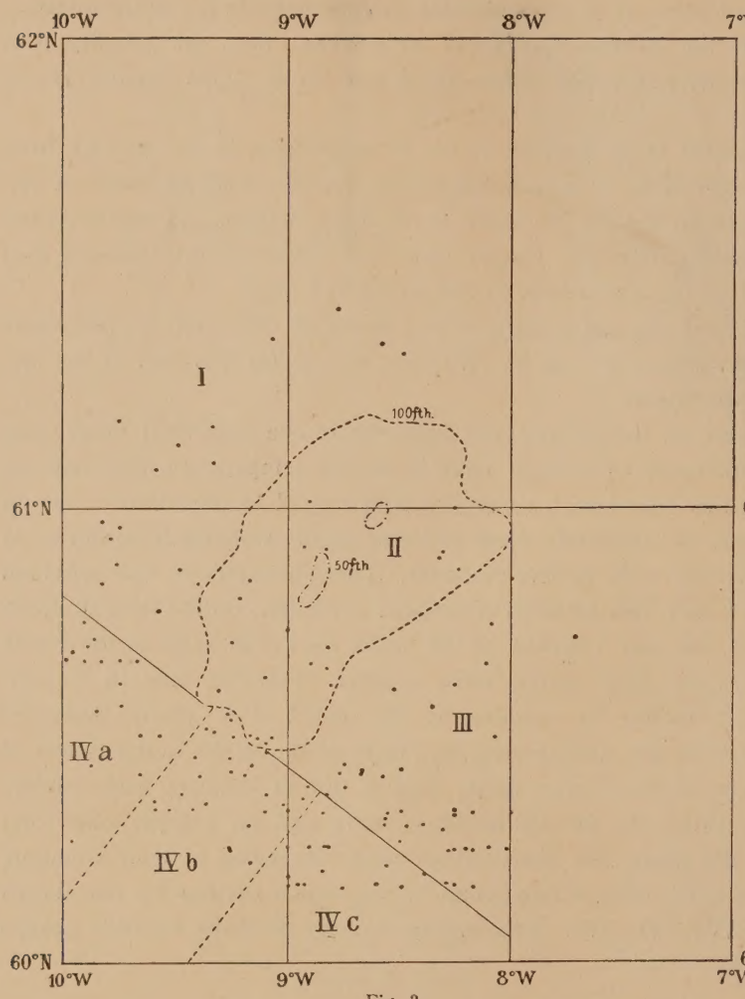


Fig. 3

We see, however, that the differences are only minimal and so variable, that if we only had this surface-material at our disposal, we should not with any certainty have been able to state the phenomenon. The surface-temperatures do not show the variation across the bank, and the same holds good with regard to the surface-salinity as well as to the temperatures on the Rockall Bank. The surface-material is too small and heterogeneous to suit this purpose.

We may, however, especially on the basis of the mentioned 3 station-series on the Faroebank with great certainty take it for granted, that the water on a bank very often shows lower temperatures and salinities than the surrounding water at the same depths, and the most natural explanation of this matter seems to be that along the sloping of the bank towards the depth, currents and mixing-processes exist which bring the deeper layers up to the bank. The shape of the 7,6 °-isotherme Fig. 2, is also in favour of this supposition. That a threshold or ridge on the sea-bed forms distinct hydrographical borders even in the uppermost layers, is a wellknown, perhaps a general rule. We need only think of the Faroe-Iceland- and Iceland-Greenland ridges and it seems very likely that an isolated bank should have effects of a similar kind, though not so well marked.

However, even if the water on a bank may frequently be a little colder and a trifle fresher than the surroundings, yet this very fact can surely not give a full explanation of the differences in the pelagic animal life and vegetation, and of the rather sharp limits which a bank seems able to place as to the occurrence of the pelagic organisms. That a rather lively reciprocal action between the bottom and the upper layers can play an essential part, seems probable, but also this hardly offers a sufficient explanation of the fact.

Of a quite peculiar interest in our section is Station 12, showing an unexpectedly great depth, namely 950 metres. Of other stations of great depth may be mentioned No. 5 with 1170 metres, No. 27

with 955 metres and No. 21 with 780 metres. In order to compare the measurements from these stations, the results have been recorded in the following table, together with the measurements from Station 50 which was taken in the Atlantic NW of the Faroe Bank on May 28th 1905.

Depth	Temperature						Salinity					
	St. 50	St. 12	St. 5	St. 27	$^{24}/_{5}$ 11 a. m. St. 21	$^{25}/_{5}$ 5 a. m. St. 21	St. 50	St. 12	St. 5	St. 27	$^{24}/_{5}$ 11 a. m. St. 21	$^{25}/_{5}$ 5 a. m. St. 21
0	8,6	8,5	8,3	8,9	8,5	8,3	35,28	35,29	35,37	—	35,22	35,24
100	3	7,6	7,8	7,4	7,1	7,2	27	24	28	35,16	20	17
200	0	2	0	6,6	6,5	6,8	27	21	20	14	12	16
300		6,8	6,7	5,3	0	5,5		21	19	07	13	09
400	7,8	5,5	0	2,9	4,3	1,7	26	12	14	34,87	00	34,84
500		2,7	4,1	1,3	1,2	0,4		02	00	84	87	88
600	7,5	0,8	1,8	0,8	0,2	0,0	25	34,94	34,91	83	87	93?
700		—0,4	0,3	—0,5	—0,1	—0,3		92	91	87	89	89
800	7,1			—0,77			23			90		
900		—0,46						92				
950	6,2			—0,80			17			91		
1000			—0,62						91			
1150			—0,67						92			

Percentage of oxygen-saturation.

Depth	St. 12	St. 5	St. 27	$^{23}/_{5}$, 4 p. m. St. 21	$^{24}/_{5}$, 8 p. m. St. 21
0	100,6	99,3	106,2		
100	95,9	96,8	98,7	96,1	92,9
200	94,9	97,3	96,3		93,6
300	2	94,9	94,9	93,5	94,1
400	91,2	4	4	94,5	92,4
500	88,1	91,7	91,2		87,8
600	85,5	89,9		85,4	85,0
700	83,4	86,0	83,8		84,7
800			83,8		
900	82,9				
950			83,7		
1000		82,6			
1150		8			

From this comparison we see that rather unmixed Atlantic water exists at the stations 12 and 5 from the surface down to a depth between 300 and 400 metres. At the stations 27 and 21 this layer is somewhat mixed with fresher water, and we see from the decrease in salinity with the depth that the deeper a sample was taken below the surface, the more it was mixed. Between 300 and 500 metres we find at the stations 12, 5, 27 and 21 a proportionately steep fall both in temperature, salinity and percentage of oxygen-saturation, and at still greater depths the highly characteristic difference appears between the water of the Atlantic station and of the other stations.

The low temperatures and salinities at greater depths show that these four stations with regard to the deeper layers quite distinctly belong to the Norwegian Sea- or Faroe-Shetland Channel area. In examining the chart, we might in advance know this with regard to the stations 5 and 21. With respect to Station 27 we might be in doubt, and Station 12 would undoubtedly have been reckoned as belonging

to the Atlantic area. By comparing the temperatures and salinities we find at the stations 12 and 5 at 400 metres considerably higher values than at Station 27, and we should undoubtedly have attributed considerable importance to this difference, if the continuous observations at Station 21 had not shown that at each single place the temperatures and salinities at the depths near the boundary layer may vary so considerably during a short period, inter alia on account of the currents produced by the tidal force. As this state of things appeared so plainly at Station 21, and as similar movements perhaps to a still higher degree may be expected at places which like the stations 5, 12 and 27 are situated at the outmost branches of the deep channel, we cannot maintain with certainty that a regional difference in hydrographical respects exists between the stations. They all show a salinity of 34,9 ‰, characteristic of the deep bottom water of the Faroe-Shetland Channel, and from 700 metres downwards temperatures below 0°. The most marked difference is, that Station 12 has a temperature of —0,5° at a depth of 900 metres, while Station 27 has —0,8°. Even if we take this difference into account, it seems most likely that the stations 12 and 27 are situated in a channel extending from the deep of the Faroe-Shetland Channel and nowhere between this and the stations broken by much shallower ridges. This supposition becomes practically a certainty, if we regard that the percentage of oxygen-saturation at equal depths is of the same value at all stations. Even at Station 12, which most probably is situated in the inner part of the rather narrow channel and far from the main deep, the percentage of saturation is 83 % just as at the other stations; and thus it does not appear as if the water in this channel is renewed less frequently than in the open main deep outside.

The great depths found at the stations 27 and 12 are far from being in accordance with the bottom-curves on Fig. 1, and we see, that our knowledge of the bottom-relief between the Faroe Shelf and the Faroe Bank is very limited, and from the preceding remarks it will be seen how far more valuable statements of depth together with analogous hydrographical observations are for judging the right shape of the bottom curves, than statements of the depth alone.

The distance between Station 12 and the great depths of the Norwegian Sea North of the Faroes is not twice as great as the distance to the part hitherto known of the deep of the Faroe-Shetland Channel; consequently we might think that Station 12 was in direct contact with the Norwegian Sea by a channel across the Faroe-Iceland Ridge. The proportionately numerous soundings on this ridge and between the Faroes and the most northern part of the Faroe Bank yet seem to show that this can hardly be the case.

At Station 27 we find at 600 metres' depth a distinct salinity-minimum of 34,83 ‰, while the salinity shows its normal value of 34,91 ‰ at a depth of 950 metres. Further a minimum of 34,84 ‰ occurs at Station 21 at a depth of ca. 400 metres, but not at all at the stations 5 and 12. From the earlier Scotch hydrographical investigations in the Faroe-Shetland Channel we see that such a minimum occurs in many cases, whilst in many others it does not. This also shows that the hydrographical conditions in the Faroe-Shetland Channel are rather heterogeneous and highly changeable from one time to another, even at great depths. The temperature of the water which carries the salinity-minimum, is in this case 1,7° at Station 21 and 0,8° at Station 27. Water of a temperature and salinity as low as these can probably only originate from the East-Icelandic polar-current, and we thus see that the water of this directly may be recognised as far from its source as at Station 27; indirectly its influence becomes of vital importance to the surrounding layers by mixing-processes, and it is undoubtedly owing to an increase of its effects in proportion to the flow of Atlantic water when we find the salinity in the upper layers South of the Faroes reduced to less than its usual value.

At Station 21 situated 60 miles East of Suderø at 61° 27' N. Lat.—4° 33' W. Long., bottom-depth 780 metres, continuous hydrographical measurements were taken for 67 hours, commencing on May 23rd at noon. The place of the station was marked by means of an anchored buoy. The force of

the wind was for the greater part of the time 3 Beaufort (scale 1—12, estimated) with magnetic direction from the W-Quadrant. The current which was estimated by the lee-way of the ship was most frequently coming from NNE, sometimes from NE and E. Its force was most frequently from $^1/_2$ to 1 mile per hour, sometimes still more. The statements are however not so complete that we may expect to find an eventual connection between the force and direction of the surface-current and the variations in temperature and salinity of the deeper layers. From the quoted data we see, however, that the component of the wind in the direction of the current was incessantly directed against the current. That the current has had the indicated direction, is in full agreement with the fact, that the salinity on Station 7 decreased in the period from May 12th till June 1st.

The temperatures and salinities have been represented graphically on Plate I, the time (local time) being indicated as abscissa, temperatures (broken line) and salinity (fulldrawn line) as ordinates. All the temperature-curves have a common zero, while each salinity-curve has its own special zero for the ordinates, as indicated on the right edge of the plate.

The main interest of the diagram is attached to the course of the curves at 300, 400 and 500 metres. Though the course is somewhat irregular, we see, however, quite distinctly a period of ca. 12 hours. The time between a maximum and the following minimum appears to be ca. $5^1/_2$ hours for the temperature-curve at 300 metres, and ca. $5^3/_4$ hours for the 400 metres' curve.

It is quite natural to connect this periodical variation with the tidal-force, and attempts have also been made to separate some tidal-periods. Through harmonic analysis was determined for each separate depth the mean-temperature $\overline{T}$ and the mean-salinity $\overline{S}$, as well as the amplitudes $2T_{M_2}$ and $2\,S_{M_2}$ and the phases ζ_T and ζ_S of the lunar-period M_2, which is usually predominant. The calculation was made according to the formulae

$$T = \overline{T} + T_{M_2} \cos 30^0\ (t - \zeta_T) \text{ referring to the temperature}$$
$$S = \overline{S} + S_{M_2} \cos 30^0\ (t - \zeta_S) \text{ referring to the salinity.}$$

For each separate depth, T is the average of the ordinates of the temperature-curve for each separate lunar-hour 0, 1, 2, ... 11 = t (see the scale on Plate I), and S has a quite analogous signification with regard to the salinity. The results are given in the following table.

Depth in metres	$\overline{T}$	T_{M_2}	ζ_T	$\overline{S}$	S_{M_2}	ζ_S
0	8,50	0,01	4,2	35,21	0,010	5,1
25	7,66	06	1,5	20	004	1,2
50	36	02	7,4	19	002	11,8
100	10	02	8,0	18	004	1,1
200	6,58	03	0	16	005	2,8
300	5,66	10	7,9	10	016	7,2
400	2,90	43	8,7	34,91	034	8,7
500	0,83	17	10,0	85	017	4,6
600	01	02	0,0	89	009	3,2
700	— 0,26	02	7,9	90	004	11,3

The variation in the mean-temperature $\overline{T}$ and mean-salinity $\overline{S}$ with the depth has been graphically represented on Fig. 4. We see that $\overline{T}$ decreases from surface to bottom, and diminishes in a specially rapid manner between 300 and 500 metres. In the upper 400 metres the salinity-curve $\overline{S}$ has about the same course, but between 400 and 500 metres a salinity-minimum of 34,85‰ is found. From this value $\overline{S}$ increases towards the bottom, rather rapidly from 500—600 metres, less from 600 metres downwards. If we compare this figure with the curves on Pl. I, it will be seen that in the layers where $\overline{S}$ and $\overline{T}$

vary strongly with the depth and where the temperature- and salinity-gradients are large, we also meet with the greatest variations (Pl. I) in the course of the time. Hence we conclude that the variations found in the intermediate layers in the course of our three days are essentially due to vertical movements in the water-volume; but we dare not of course extend this also to hold good for longer periods, and it is probable that considerable horizontal movements, periodical and unperiodical, occur together with the vertical movements.

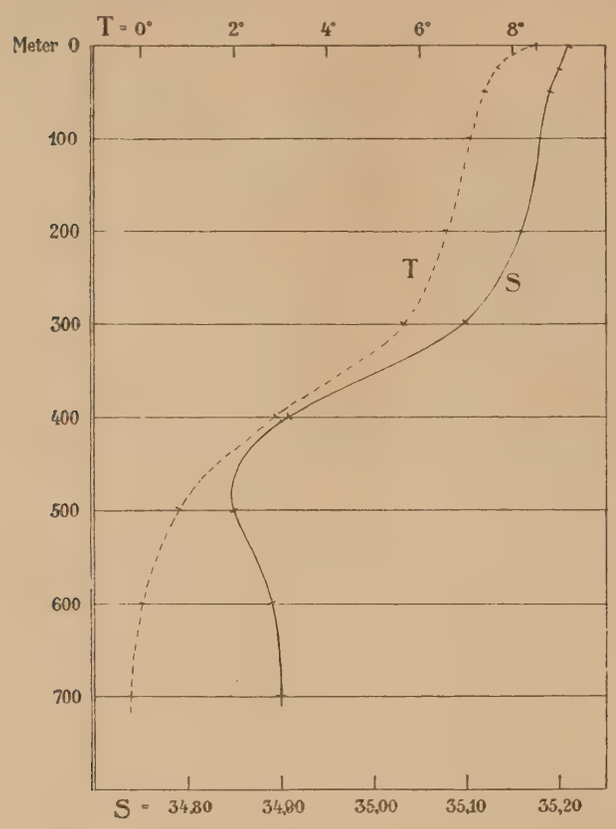


Fig. 4

In the upper 200 metres' layer, where the vertical gradients are small and where the vertical movements cannot be of great importance, the harmonic analysis has given amplitudes which for the temperature are only a few hundredths of a degree and for the salinity less than 1 hundredth pro mille. At these dephts the phases do not quite agree with each other, and this also shows that the tidal-force has only a very slight or no traceable influence on the variations in temperature and salinity. However, this does not mean that the tidal-force has no influence on the movements of the water; it is on the contrary very likely that periodical horizontal currents occur, but we have not been able to ascertain this by the present observations.

On the other hand, the influence of the tidal-force on the variations in temperature and salinity is quite obvious at 300, 400 and 500 m. This is evident from Fig. 5; the black dots indicate the averages of the observations to the different lunar-hours, on which the calculation is based, and we see that the periodicity is distinct. The calculated cos-curves (broken lines) very well represent the series of the empiric averages.

As already said, the salinity is at 500 and 600 metres increasing downwards, while the temperature is decreasing. At these depths vertical movements must consequently cause the temperature and salinity to change in opposite directions during a tidal-period, quite in accordance with the curves for the two depths on Plate I. The same appears by the harmonic analysis, as at 400 metres we find the same value 8,7 lunar-hours for the temperature-phase ζ_T and for the salinity-phase ζ_s, while at 500 metres we find $\zeta_T - \zeta_s = 5{,}4$. If this phase-difference had been 6, we should have had the complete contrast between the two curves, and thus we must conclude, that the variations in temperature and salinity at 500 metres are produced by vertical movements as well as at 400 metres.

Comparing the curves Fig. 5 for the different depths, we find a distinct delay of the phase from 300 to 500 metres, the temperature-maximum at 300 metres coming 2,1 lunar-hours before the maximum at 500 metres. Also with regard to the salinity-curves the same holds good, if we remember that the downwards moving of the water, which produces temperature-maxima at all depths, will produce salinity-maxima at 300 and 400 metres, but a salinity-minimum at 500 metres. Thus the figures show that when the vertical oscillation of the water at 300 metres changes from sinking to rising, then at 500 m. it still has a considerable velocity downwards. That this only can take place when horizontal currents occur at the same time, is a matter of course.

At 600 and especially at 700 metres, the temperature- and salinity-gradients are very small, and

for these depths we find the same as for the upper layers: small and irregular variations in the course of time. At 600 metres the harmonic analysis gave a temperature-amplitude $2T_{M_2} = 0{,}04^0$ and a salinity-amplitude $2S_{M_2} = 0{,}02\,‰$, while the analogous values for 700 metres were found to be $2T_{M_2} = 0{,}04^0$ and $2S_{M_2} = 0{,}01\,‰$. Thus the influence of the tidal-force on the variations in temperature and salinity is very slight, but this does by no means exclude a considerable influence both on the currents (that

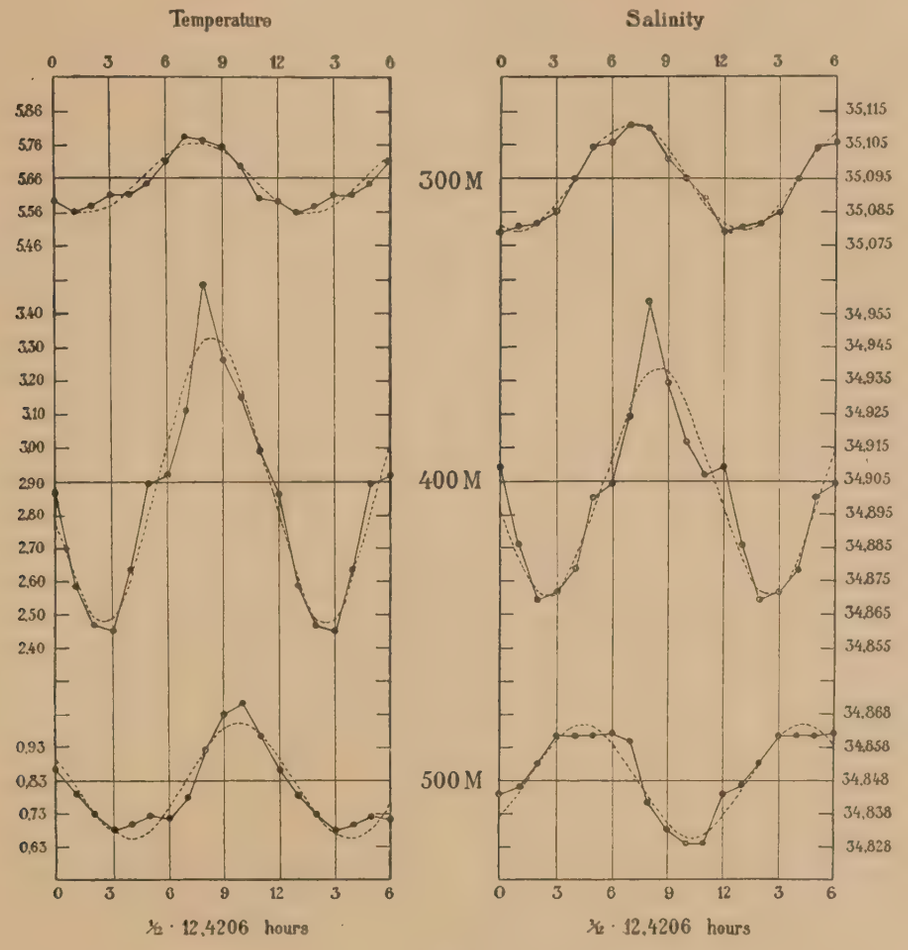


Fig. 5

means: horizontal movements) in the water-volumes at the bottom and on the vertical movements; the intensity of the vertical oscillations must increase with the distance from the bottom where the intensity of course is zero.

As the influence of the tidal-force on salinity and temperature is greatest at 400 metres, we have at this depth made the variations subject to a closer investigation. It is a well-known fact that the effects of the solar-period S_2 may be rather considerable at some places, and as a glance at Plate I would seem to show, that the main-period is somewhat shorter than the lunar-period of 12,4 solar-hours, it was natural to determine the constants for the period whose length is equal to that of the solar-period. These constants marked S'_2 are compared with the constants of the lunar-period in the following table.

Constants at 400 metres' depth.

	Temperature	
	$\bar{T}$	R
M_2	2,90	0,43
S'_2	2,92	0,44
11,4	—	0,38
	Salinity	
	S $^0/_{00}$	
M_2	34,905	0,034
S'_2	34,906	0,035
11,4	—	0,029

The amplitudes 2R are almost equally great for the lunar- and the S'_2-period, and hence we see that the somewhat shorter solar-period is in reality unable to separate a period with an essentially greater amplitude than that of the lunar-period, which we might be tempted to think merely by a glance at the curves of the plate. As a further proof that the apparent periodicity with shorter period is nothing but delusion, the amplitude was calculated for a period of 11,4 solar-hours, the curve apparently showing this to be the time which elapses on an average between two maxima. This period, the amplitudes of which have also been recorded in the table above, gave essentially lesser values than S'_2 and M_2, so that we must feel justified in concluding that M_2 or S'_2 is the main-period, and that casual variations have got no rhythmical character with shorter periods.

As the investigations have only lasted 67 hours, and as the difference in time between the lunar- and the solar-period is so slight, we cannot by our usual method, which has furnished the figures of the table, separate M_2 from the true S_2. It would thus be quite misleading to conclude that the temperature really has a lunar-amplitude of $2 \times 0{,}43^0$, while the solar-amplitude at the same time is $2 \times 0{,}44^0$, and that these amplitudes may be added together. In order to get the two periods separated, the following method was employed, which however was carried out only with regard to the temperatures at 400 metres. From the temperature-curve of the plate, the temperature T was read off for each lunar-hour, together 60 values; of these the mean-value $\bar{T}$ was formed, and then again $T - \bar{T}$ for each separate lunar-hour; then we write:

$$T - \bar{T} = a \cos(\alpha t - \varphi) + b \cos(\beta t - \psi).$$

From the 60 equations of this form a, φ, b and ψ were determined, using the method of the least squares. For αt the value $p \cdot 30^0$ was used, p being the running number of the determination; βt was put equal to $p \cdot \frac{30}{28{,}984} 30^0 = 31{,}052^0$, a meaning half the amplitude of the lunar-period and b half the amplitude of the solar-period, while φ and ψ respectively mean the lunar- and the solar-phases. The calculation gave $a = 0{,}248$, $b = 0{,}498$, $\varphi = 177^0 = 5{,}9$ lunar-hours, $\psi = 324^0 = 10{,}8$ solar-hours.

According to this calculation, the amplitude of the solar-period should be twice as great as that of the lunar-period. That a formula with 4 constants can better render the existing oscillations than a formula with 2 constants, we know in advance; we may however wonder that the amplitudes have become so great as is the case here. The solar-amplitude alone is according to this calculation $1{,}00^0$, while the ordinary harmonic analysis gave $0{,}88^0$ for the same amplitude. The two cos-curves M_2 and S_2 have been represented graphically on Pl. II, the amplitudes 2a and 2b as well as the phases φ and ψ having the values just found. The phase-difference $\psi - \varphi$ is 4,6 lunar-hours at full-moon. This phase-difference which means that spring-tide should occur about 6 days after full-moon, is greater than might be expected, the analogous phase-difference for the sea-level being in Thorshavn only ca. 1 hour [1]).

[1]) C. Crone: Flux et Reflux des Mers qui environnent le Danemark, etc. Institut Météorologique de Danemark, Rapport sur les travaux du service maréographique, Copenhague 1906, pag. 30.

It thus appears as if amplitudes as well as phases have obtained values which, owing to the shortness of the series of observations, ought to be looked upon with some distrust. A uniform change in the magnitude of the temperature-gradient will thus produce a continuous change in the temperature-amplitudes found, and then the total temperature-variation might just be represented by two cos-functions like the ones employed. The values found can, however, by no means be characterized as impossible or entirely wrong, and the total result of the two periods has therefore been graphically represented on Pl. II as the $M_2 + S_2$ - curve.

A study of the curves on Pl. I, especially the 400 metres' curve, leads to the supposition, that a period of about 24 hours also exists in the variations. By the ordinary harmonic analysis the constants of the O-period at 400 metres were thus determined, with the following result:

O-period of temperature: $\overline{T} = 2{,}98^0$ $R_T = 0{,}24^0$ $\zeta = 17{,}8 \cdot {}^1/_{24}$ O.
O-period of salinity: $\overline{S} = 34{,}910\ ‰$, $R_S = 0{,}019\ ‰$, $\zeta = 16{,}2 \cdot {}^1/_{24}$ O.

We see that the amplitudes R are as great as for the lunar-period just found thus by no means inconsiderable. The phases have been referred to May 23rd at 12h m. local time, so that the temperature-maximum occurs $17{,}8 \times {}^1/_{24}$ O, and the salinity-maximum $16{,}2 \times {}^1/_{24}$ O after this moment; the curve is graphically represented on Pl. II. The entire series of observations being hardly 3 times as long as the O-period, we can naturally not draw any safe conclusions with regard to this tide on the basis of a space of time so comparatively short; and nearly the whole amount of the variation expressed by our O-constants may perhaps be due to casual variations which have obtained a certain rhythmical character during our three days.

The determination of the constants are at any rate to be regarded as extremely uncertain. The magnitude of the amplitude shows, however, that on future investigations of this kind and in these waters it will be necessary to take the O-period into account; and if it is refound in a future material with the same strength as here, we shall have every reason to believe in its existence and importance.

On Pl. II a curve $M_2 + S_2 + O$ has been drawn, indicating the result of the co-operation between the different tidal-forces, and for the sake of comparison the observed temperature curve »T obs.« is also represented. We see a quite satisfying agreement between the two curves.

As a result of this investigation of the influence of the tidal-force on the temperature at the depth of 400 metres may be set forth, that the variations calculated must partly be ascribed to the tidal-forces, that the lunar-period M_2 undoubtedly plays an essential part, and that the periods S_2 and O probably enter into the variations with amplitudes, which are not inconsiderable in proportion to M_2.

If we compare the $M_2 + S_2 + O$-curve Pl. II with the observed temperature-curve, we find that if the periodical variations be taken away from the observed curve, very essential variations still remain (see the lowest curve on Pl. II). These variations might possibly be partly ascribed to other tidal-forces which we have been unable to include here, but if we consider that the periods M_2, S_2 and O are usually the most active, and that the amplitudes which have been found for them here are probably too great, it will be understood that it is quite necessary also to take casual variations into account. That they probably may be more considerable than the periodical ones, will be understood from the following remarks.

In the table below is recorded a comparison of the temperature-amplitudes $2\ T_{M2}$ and $2\ S_{M2}$ found by means of the harmonic analysis, the difference $T_{max} - T_{min}$, between the highest and lowest temperature observed in the course of the three days, and the analogous difference $S_{max} - S_{min}$ in salinity. The comparison is thus analogous to a comparison between the yearly variation in the air-temperature and its extreme values.

Depth in metres	$2T_{M_2}$	$T_{max} - T_{min}$	$\frac{2T_{M_2}}{T_{max} - T_{min}}$	$2S_{M_2}$	$S_{max} - S_{min}$	$\frac{2S_{M_2}}{S_{max} - S_{min}}$
0	0,02	0,80	0,0	0,019	0,070	0,3
25	11	60	2	008	070	0
50	04	30	1	004	060	1
100	04	50	1	007	060	1
200	06	70	1	010	080	1
300	21	1,00	2	031	150	2
400	85	2,70	3	067	220	3
500	34	1,00	3	034	080	4
600	04	0,40	1	017	080	2
700	03	30	1	007	050	1

From this table we see that the changes in temperature and salinity due to the tidal-forces are at any rate considerably smaller than $T_{max}—T_{min}$ and $S_{max}—S_{min}$. The proportions $\frac{2T_{M_2}}{T_{max}—T_{min}}$ and $\frac{2S_{M_2}}{S_{max}—S_{min}}$ show a marked variation according to the depth. Both proportions are at 300 metres equal to 0,2, at 400 metres equal to 0,3, and at 500 metres equal to 0,3 and 0,4; at all other depths they are less. In this way it may also be seen that the tidal-forces exercise the greatest influence on the changes of temperature and salinity at 300—500 metres, where the temperature as well as the salinity are changed most quickly with the depth, and where the best opportunity for vertical motions of the water-volumes is found.

And yet it will be seen, that even at 400 metres the changes due to the tidal-force do not amount to more than $^1/_3$ of the total variations occuring. This can, of course, partly be explained by the circumstance, that only one tidal-period M_2 has been taken into account. But even if S_2 and O had also been regarded, the proportion would not much exceed $^1/_2$, and it is not probable that it would be much increased if we included the other tidal-periods.

As mentioned before, the variations in temperature and salinity in the boundary-layer can hardly be explained without presuming vertical movements to take place in the water-volumes. At 400 metres where $2T_{M_2} = 0{,}85^0$, this oscillation would be produced by a vertical motion of about 35 m in the water-volumes, while the greatest variation found in the temperature would demand a vertical motion exceeding 100 metres. The variations in salinity yield very nearly the same values. It is highly probable that the tidal-forces really produce vertical oscillations or internal waves of a height of 30—40 metres, combined with horizontal currents in the water-volumes above and below the boundary-layer. But it is on the other hand very doubtful, whether the maximum-variations which are vertical movements of the isothermes and isohalines, should also be regarded as vertical movements of the very water-volumes. It is to be remembered that the irregular variations may in part very well be ascribed to horizontal currents carrying heterogeneous water past the place of observation.

The 0-meter's curve shows (Pl. I) that a slight daily period can be traced in the temperature, this being by night ca. $0{,}3^0$ lower than by day. The temperature decreased moreover almost 1^0 in the course of the afternoon and the night between May 23rd and 24th, although the temperature of the atmosphere was 1^0 to 2^0 higher than that of the water. Thus a difference of 1^0 between the surface-temperatures at different places of these waters need not necessarily mean more than the changes occurring in the course of some hours at one and the same place.

The surface-salinity has varied somewhat irregularly. The said decrease of 1^0 in the temperature was accompanied by an increase in salinity of ca. 0,05 ‰, thus the reverse of what we perhaps might have expected. The unusually low surface-salinity on May 26th at 1. a. m. is in the original journal explained by rain, and three hours later the surface-salinity was found to be 32,99 ‰ in »pouring

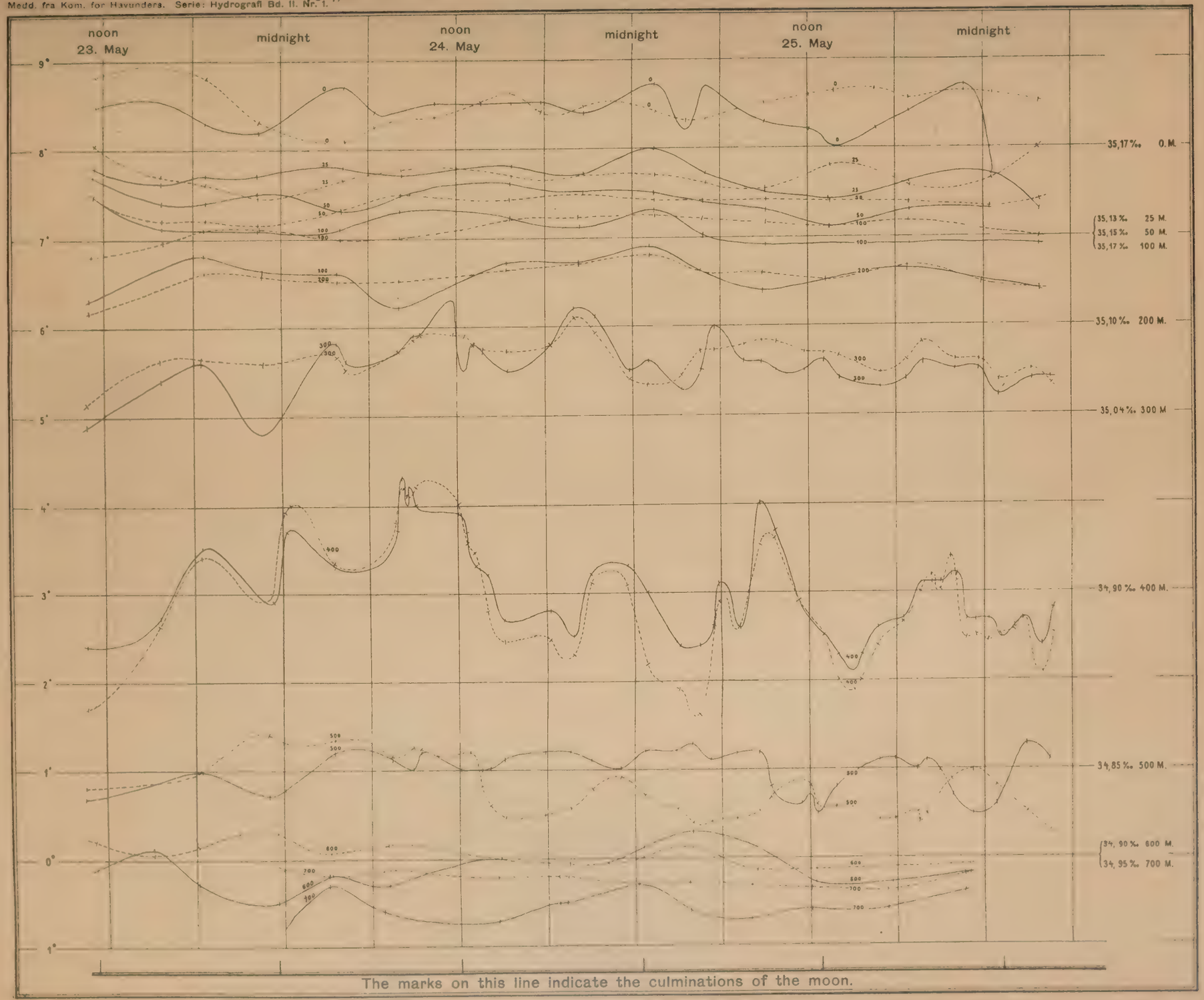
rain«. However, the surface-samples were taken with a bucket, which probably had not been rinsed sufficiently with sea-water.

At 100 and 200 metres the temperature and salinity are more regular than at the surface. The difference between the highest and lowest temperature is some tenths of a degree, the changes occur simultaneously at the two depths and give the curves a rather regular undulating shape. The variations in salinity are extremely slight at a depth of 100 metres; at 200 metres they are somewhat greater, the difference between the highest and lowest value being 0,07 ‰. Further the variations in salinity to some extent accompany the variations in temperature, a high temperature thus corresponding with a high salinity and vice versa. But as mentioned before, these apparent regularities of the upper layers did not give any certain result by the harmonic analysis.

Medd. fra Kom. for Havunders. Serie: Hydrografi Bd. II. Nr. 1.

Continuous observations of temperature and salinity

from the S/S „Thor" in the Färoe-Shetland Channel, on the 23.—26. of May 1910.



The figures on the curves indicate the depths. The distance between two horizontal lines corresponds to 1 ° centigrade of temperature and to 0,10 °/₀₀ of salinity. The salinity curve for say 100 meters is referred to the horizontal line marked 100 M. on the right hand side of the plate; to get the salinity at 100 meters, find the ordinate of the curve reckoned from the said horizontal line as axis of abcissae, and add 35.17 °/₀₀. The vertical lines indicate the local time.

Tidal Variation of the Sea-Temperature

From Observations in the Färoe-Shetland Channel at 400 Meter, on the 23.—26. of May 1910.

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